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Abstract

Vertical velocity and reflectivity data obtained with the SOUSY-VHF-Radar located in West Germany have been compared with the operational analysis data from the European Centre for Medium-range Weather Forecasting, with radiosonde data from nearby stations, as well as the standard synoptic weather maps for the region. Also, the effects of precipitation on VHF and UHF wind profiler data have been investigated. Results have shown that the radar reflectivities at 6 m wavelength are enhanced at the height where the frontal inversion is located. The UHF echoes are dominated by precipitation, even when the rainfall is light, while VHF echoes have nearly equal contributions from precipitation and the "clear air," even when the rainfall is heavy. Comparison of the radar vertical velocities and the radiosonde data have made it possible to show the vertical circulations around several fronts. The results are in general agreement with the expected patterns of ascent in the warm air and descent in the cold sectors, but the detailed structures are more complicated and show a banded structure and a significant indirect circulation in connection with the fronts. Comparison of the operational analysis vertical velocities from the European Centre and the SOUSY-VHF-Radar vertical velocities shows that some of the same features are reproduced in both data sets, but there are discrepancies with differences of up to half a day between the times of the appearance of the vertical velocity structures connected with fronts and jet stream passages over the radar.

4

COMPLETED PROJECT SUMMARY

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PRINCIPAL INVESTIGATOR: Prof. M. F. Larsen
Department of Physics & Astronomy
Clemson University
Clemson, SC 29631

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PUBLICATIONS:

1. Cornish, C. R., and M. F. Larsen, A review of synoptic scale wave perturbations in the equatorial stratosphere, J. Atmos. Terr. Phys., 47, 769-780, 1985.

2. Larsen, M. F., and J. Röttger, Observations of frontal zone and tropopause structures with a VHF Doppler radar and radiosondes, Radio Sci., 20, 1223-1232, 1985.

3. Larsen, M. F., and J. Röttger, A comparison of thunderstorm reflectivities measured at VHF and UHF, J. Atmos. Ocean. Tech., 4, 151-159, 1986.

4. Larsen, M. F., R. F. Woodman, T. Sato, and M. K. Davis, Power spectra of oblique velocities in the troposphere and lower stratosphere observed at Arecibo, Puerto Rico, J. Atmos. Sci., 43, 2230-2240, 1986.

5. Larsen, M. F., J. Röttger, and D. N. Holden, Direct measurements of vertical velocity power spectra with the SOUSY-VHF-Radar wind profiler system, J. Atmos. Sci., 44, 3442-3448, 1987.

6. Larsen, M. F., J. Röttger, and T. S. Dennis, A comparison of operational analysis and VHF wind profiler vertical velocities, Mon. Wea. Rev., 116, 48-59, 1988.

7. Röttger, J., and M. F. Larsen, UHF/VHF radar techniques for atmospheric research and wind profiler applications, Battan Memorial and 40th Radar Meteorological Conference Volume, American Meteorological Society, Boston, in press, 1989.

8. Larsen, M. F., and J. Röttger, A comparison of thunderstorm reflectivities measured at VHF and UHF, Proceedings of the URSI/SCOSTEP Workshop on Technical Aspects of MST Radars (Oct. 21-25, 1985), Handbook for MAP, 20, University of Illinois, 279-287, 1986.

9. Röttger, J., M. F. Larsen, H. M. Ierkic, and T. Hagfors, Need for a subtropical wind profiling system, Proceedings of the URSI/SCOSTEP Workshop on Technical Aspects of MST Radars (Oct. 21-25, 1985), Handbook for MAP, 20, University of Illinois, 86-89, 1986.

10. Dennis, T. S., M. F. Larsen, and J. Röttger, Observations of mesoscale vertical velocities around frontal zones, Proceedings of the URSI/SCOSTEP Workshop on Technical Aspects of MST Radars (Oct. 21-25, 1985), Handbook for MAP, 20, University of Illinois, 35-43, 1986.

11. Holden, D. N., C. W. Ulbrich, and M. F. Larsen, UHF and VHF observations of thunderstorms, Proceedings of the URSI/SCOSTEP Workshop on Technical Aspects of MST Radars (Oct. 21-25, 1985), Handbook for MAP, 20, University of Illinois, 288-292, 1986.

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13. Holden, D. N., and M. F. Larsen, Observations of thunder with the Arecibo VHF radar, Proceedings of the URSI/SCOSTEP Workshop on Technical Aspects of MST Radars (Oct. 21-25, 1985), Handbook for MAP, 20, University of Illinois, 147-152, 1986.

14. Larsen, M. F., J. Röttger, and T. S. Dennis, Comparison of vertical velocities analyzed by a numerical model and measured by a VHF radar over an eleven day period, Proceedings of the URSI/SCOSTEP Workshop on Technical Aspects of MST Radars (Oct. 21-25, 1985), Handbook for MAP, 20, University of Illinois, 44-47, 1986.

ABSTRACT OF OBJECTIVES AND ACCOMPLISHMENTS:

Objectives included an analysis of errors in UHF and VHF radar wind profiler measurements of vertical velocities and potential errors associated with tilting of isentropic (specular reflection layers) and scattering from precipitation. Additional goals included the comparison of radar vertical velocities with the analysis from the European Centre's operation analysis, and the determination of the vertical circulations around a series of cold fronts, warm fronts, occlusions, and one tropopause fold that passed the SOUSY-VHF-Radar located in West Germany.

Our results have shown that radars operating at frequencies close

to 400 MHz, the frequency of the proposed operational network, will be dominated by scattering from precipation even for small rainfall rates. Thus, vertical velocity measurements with 400-MHz systems are essentially impossible when there is precipitation in the environment. Radars operating at frequencies close to 50 MHz have approximately equal contributions from precipitation and turbulent scattering, and the two components can be separated in the frequency spectra. Therefore, 50 MHz systems can measure vertical air motions in virtually all conditions.

The observations of vertical circulations in frontal zones have shown a distinctive banded structure that includes a strong indirect circulation component in all the warm and cold fronts that passed the radar site. The exceptions included two occlusions which showed no evidence of an indirect circulation. The vertical velocity patterns of ascent and descent were in agreement with expectations in an average sense, but the strongest ascent and descent was highly localized. The variance of the radar data and the vertical velocity from the European Centre's operational analysis agreed well in magnitude. Many of the same features, although not all of the vertical velocity bands, were evident in both time series, but the timing of the passage of the bands varied by as much as 12-24 hr between the two sets of values. The tropopause folding event showed strong descent on each side of the frontal location near the tropopause, in agreement with the circulation proposed earlier by Danielsen, but the two shafts of strong subsidence were aligned much closer to the vertical than the frontal zone itself. The latter finding is different from the conventional picture of the vertical circulation near tropopause folds and is of interest to the extent that the observation is representative of more cases than the one that occurred over the SOUSY radar.

We have analyzed the tilt of isentropic (specular) surfaces based on the phase information derived from the spaced antennas of the SOUSY system. The results show surface tilts of 2-3 degrees or less, in general agreement with expectations, but the largest tilts are located in the frontal zones. The tilts imply that a correction needs to be made in VHF vertical velocity measurements due to the contamination of the vertical beam, line-of-sight velocity by the horizonal wind component. The tilt measurements also show the potential of the radars for measurements of the baroclinicity in actively developing frontal zones.

Final Technical Report

AFOSR-85-0216

STUDIES OF FRONTAL ZONE DYNAMICS WITH A HIGH-RESOLUTION WIND PROFILING SYSTEM

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January 1989

1. Introduction

The goal of the research project has been to use the relatively new wind profiler wind measurement technique to study the dynamics and vertical circulations around frontal zones, as well as to investigate the potential operational applications of the profiler data. The excellent time and height resolution afforded by the radar measurements provide details in the horizontal and vertical wind fields that would ordinarily be missed in studies using conventional meteorological balloons or aircraft. While the data open new areas of mesoscale dynamics for investigation, we still have to be careful about possible contamination of the velocity data when specular echoes or scattering from precipitation are involved. For instance, if precipitation provides the dominant scattering mechanism, the radar vertical velocity will not be representative of the vertical air motion. Specular echoes may contaminate the vertical velocity data, too, if the temperature gradient that is producing the enhanced echoes moves with a velocity different than the air velocity. We have pursued two topics of investigation during the grant period. The first deals with the echoing mechanisms and the effects on radar wind profiler measurements. The second deals with the vertical circulation around fronts and the relationship to frontogenetic and frontolytic processes. The study has been carried out using a combination of standard meteorological radiosonde data, operational analysis data from the European Centre for Medium-range Weather Forecasting (ECMWF), and data from several frontal passage observations made with the SOUSY-VHF-Radar operated by the Max-Planck-Institut in the Hartz Mountains, West Germany. We have also used a small data set from the UHF radar at Arecibo to compare the effects of precipitation on profiler measurements at the two frequencies. The higher frequency is very close to the frequency that will be used for the operational network in the United States, but the lower frequency has advantages in that it is less sensitive to precipitation and more sensitive to the atmospheric temperature structure.

The research effort has focused on detailed comparisons of reflectivities calculated from radiosonde data and measured with the VHF radar during five separate frontal passage events; an evaluation of the two radar frequencies commonly being considered for the proposed operational wind profiler network, i. e., 400 MHz and 50 MHz; an investigation of the vertical circulation around occlusions, a tropopause fold, and several cold and warm fronts during March 1981, November 1981, February 1982, and April 1984; a comparison of radar vertical velocities and ECMWF operational analysis vertical velocities during a three-day period in March 1981, an eleven day period in November 1981, and a five-day period in April 1984; and an analysis of the power spectra of vertical velocities at time scales from 2 hr to 15 days. The details of most of the research are described in the articles cited in the list at the end of the report, copies of which are attached. Highlights of the results are given below.

Two graduate students, Mr. Steve Dennis and Mr. James Yoe, have worked on the project and have been supported by the grant. Other graduate students, including Mr. Dan Holden, Mr. Tim

Marshall, and Ms. Amanda Clark, have helped with computer calculations, although their support has come primarily from other sources within the Department of Physics and Astronomy at Clemson.

2. Summary of Results

Details of the results can be found in the preprints and reprints given in the list of cumulative publications at the end of the report. The highlights are as follows:

a. Frontal zone reflectivities

A set of five separate SOUSY-VHF-Radar observations during times of frontal passages have been accumulated since 1977. We made a detailed comparison of radar reflectivities and potential refractivities calculated from radiosonde data and showed that a VHF radar operating at a wavelength near 6 m can detect the location of frontal boundaries above the boundary layer. There is an enhancement in reflectivity at the frontal boundary temperature inversion just as there is at the tropopause inversion when long radar wavelengths, such as 6 m, are used to probe the atmosphere. The article describing these results has been published in Radio Sci. (Larsen and Röttger, 1985).

b. Reflectivities in precipitating environments

A comparison of reflectivities in thunderstorm environments observed with the Arecibo Observatory 70-cm radar and the SOUSY 6-m radar was carried out. The two wavelengths are of particular interest because they are primary candidates for the proposed national wind profiler network. Our observations and calculations have shown that the reflectivities for precipitation and turbulent scatter are comparable at VHF but that the precipitation echoes dominate at UHF. Thus, it is possible to measure vertical air motions even in precipitating environments at the longer wavelength, but no vertical velocity measurements will be possible at the shorter wavelength, even in light stratiform rain. More quantitative descriptions and comparisons are given in the articles by Larsen and Röttger (1986a,b) which have been published in the Journal of Atmospheric and Oceanic Technology and in the MAP Handbook series.

c. Mesoscale vertical velocities

A comparison of conventional meteorological analyses based on radiosonde data and the vertical velocity measurements made with the SOUSY radar over a fifteen day period in November 1981 was completed. The results are described in the articles by Larsen et al. (1986, 1988) and Dennis et al. (1986) which have been published in Mon. Wea. Rev. and in the MAP Handbook series. Our results show that 1) the vertical circulation around two observed occlusions is stronger than would have been expected and show no indirect circulation component, 2) the vertical velocities around a tropopause fold were found to be in agreement with the model proposed by Danielsen in which there is strong subsidence along the fold and ascending air on the sides, although the indirect circulation component in the one observed event was significant, 3) the velocities around the observed cold front showed a banded structure, similar to that predicted by a number of modeling studies, and a strong indirect circulation component not predicted by the models. The latter would tend to maintain the intensity of the front. In general, the average vertical velocities around the frontal zones have the direction expected, i. e., rising motion on the warm side and sinking motion on the cold side of the front, but the structure observed by the radar is banded. The strongest vertical velocities occur in narrow regions.

d. Operational analysis and radar comparison

The analyzed vertical velocities produced by the ECMWF numerical model and the vertical velocities measured by the SOUSY-VHF-Radar in March 1981, November 1981, and April 1984 have been compared. The results are described in more detail in the papers by Larsen et al. (1986, 1988) which have appeared in Mon. Wea. Rev. and in the MAP Handbook series. Our results have shown that the normal mode initialization method used by ECMWF to carry out their operational analysis produces vertical velocities with amplitudes and variances comparable to the amplitudes and variances in the vertical velocities measured by the radar, if the radar data are averaged over 6 hr. The amplitudes and variances of the radar data increase when smaller averaging intervals are used. In an earlier study, Nastrom, Gage, and Ecklund used gridded NMC data and calculated the vertical velocity with the quasi-geostrophic omega equation, the adiabatic method, and the kinematic method. All of their calculated velocities were smaller than the measured values by factors of three or four.

The comparison of individual features in our study showed similarities in the broad features of ascent and descent, but the timing of the individual features with characteristic time scales of 12-24 hr was inconsistent between the operational analysis and the radar measurements. The timing error ranged from a few hours to as much as one day. The largest discrepancies between model and observations occurred at times of frontal passages. It may be impossible to resolve these differences completely until a network of wind profilers is available since the measurements from a single radar averaged over time cannot give the same information as the data from a network of observation sites at a given instant.

e. Vertical velocity spectra

The SOUSY vertical velocities measured during November 1981 were used to calculate the frequency and vertical wave number spectra. The results are described in the articles by Larsen et al. (1986, 1987) which have appeared in J. Atmos. Sci. and the MAP Handbook series. The recent controversy over the dynamics underlying the observed mesoscale power spectra can only be resolved by considering spectra of parameters other than the horizontal velocity. The vertical velocity spectra show a frequency spectral slope of -1 from periods of 2 hr to 15 days in the troposphere. This result is not in agreement with the predictions of the simple universal gravity wave spectrum model, but it remains to be seen if a model that includes the effects of Doppler shifting of the gravity waves can account for the steepness of the slope. The spectrum in the lower stratosphere shows a slope of -1 at higher frequencies, as well, but periods greater than the inertial period are characterized by a slope closer to zero. Since waves with periods less than the inertial period cannot propagate vertically under typical conditions, the implication is that the mesoscale spectrum at higher altitudes is dominated by gravity wave motions with frequencies greater than the inertial frequency. The drop-off in power at longer periods is due to the trapping of the energy in the troposphere. A consequence must be that the dynamics at periods from approximately half a day and out to several days must be significantly different in the troposphere and lower stratosphere.

The spectra from the radar observations have also been compared with the spectra calculated from the vertical velocities produced by the ECMWF operational analysis. The spectra agree well in amplitude and spectral slope for periods greater than approximately 2 days, but there are discrepancies at shorter periods with the analysis producing too little energy at the higher frequencies. The details of the comparison have been described by Larsen et al. (1987). We expect that the radar data will be useful in fine-tuning operational analysis procedures in the future as the numerical forecast models attain greater spatial resolution.

The vertical wave number spectrum shows a slope between -1 and -1.5, which is shallower than the slope of -2.5 expected from the simple universal gravity wave theory. Information of this kind will be important to theorists, if we are to understand the transport of energy in the mesoscale range.

f. Study of layer tilts

Some of the discrepancies between the analyzed and observed vertical motions are no doubt due to insufficient sampling resolution in the operational network and differences between the radar single-point samples and the analysis which is effectively an average over four adjacent grid points. Another problem is that there are potential errors in the radar vertical velocity measurements associated with tilting of the refractive index layers. The strongest contribution to the radar reflectivities will come from the direction perpendicular to specular layers of the type associated with the tropopause and frontal boundary temperature gradients. The layer tilts are estimated to be a few degrees at most, but generally the tilt direction will be within the radar beamwidth. Therefore, a vertically-pointing radar beam will have an effective off-vertical pointing angle. The latter effect results in a contamination of the "vertical" line-of-sight velocity component by the projection of the horizontal velocity on the effective beam direction.

The velocity error is only a small fraction of the horizontal velocity component, but the error in the relatively small vertical velocity component can be significant, even for tilts of only 2° and horizontal velocities of 10-20 m/s. The spaced antenna system of the SOUSY radar is capable of measuring the layer tilts, something that the conventional Doppler wind profilers cannot do, by using the phase differences between the signals in the three separate receiving antennas. We have calculated the tilts for the five-day observation period in April

1984. The results are shown in Figure 1 in the form of contours of constant layer tilt. The largest tilts between 1°-2° occur in the latter half of the observation period in connection with the passage of a cold-front/warm-front sequence. In fact, the largest angles occur in the cold sector between the two fronts. The corresponding corrections for the measured vertical velocities during this period would have been as large as 1 m/s which is significant when typical vertical velocity magnitudes are considered.

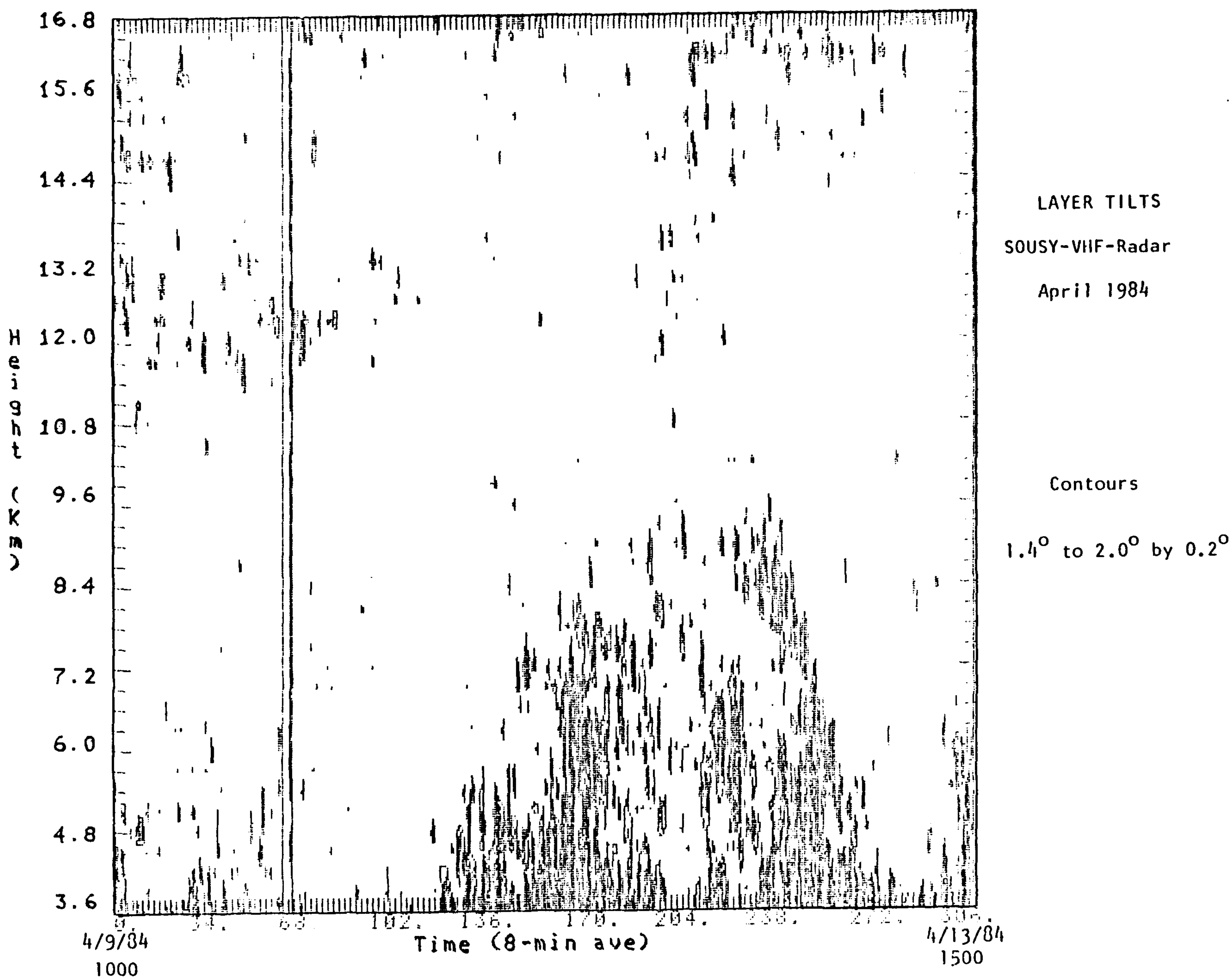
3. Conclusions and Summary of Needed Future Work

Our studies over the past three years have shown that the profiler wind measurement technique can and probably will have a significant impact on mesoscale meteorology. The instrument is an important addition to the array of measurement capabilities already available because it provides very high time resolution data over extended periods and turbulence and vertical velocity parameters which are not available from other systems. Our measurements have provided insight into the frontal zone circulations which have been found to have larger indirect circulation components than expected. Also, the largest vertical mass fluxes have been found to be very localized and embedded within banded structures.

Future studies will have to address the use of the radar measurements for fine-tuning operational analysis procedures and for deriving improved parameterization schemes for numerical modeling. For example, the vertical fluxes of heat and momentum produced by model parameterizations should be consistent with the fluxes implied by the observed banded structure and strong localized circulations seen in the radar data.

Finally, errors in the radar measurements associated with layer tilts have to be taken into account in future studies of radar vertical velocity measurements, especially because the largest tilts occur near frontal zones where the vertical circulations are of great interest. Our study only encompasses an assessment of the tilts for a single, relatively weak frontal system. More case studies are needed to determine the severity of the problem when more intense frontal systems are observed.

A related issue that we have not addressed is the potential for using the information on layer tilts to determine the baroclinicity in developing cyclonic systems. The two quantities are expected to be related since the layers are believed to be isentropic surfaces, and the tilts of such surfaces will be an indication of the baroclinicity, particularly when coupled with conventional radiosonde data.



16.8
15.6
14.4
13.2
12.0
10.8
9.6
8.4
7.2
6.0
4.8
3.6
Height (Km)
0.
34.
68.
102.
136.
170.
204.
238.
272.
306.
4/9/84
1000
Time (8-min ave)
4/13/84
1500
LAYER TILTS
SOUSY-VHF-Radar
April 1984
Contours
1.4° to 2.0° by 0.2°

Cumulative List of Papers

1. Cornish, C. R., and M. F. Larsen, A review of synoptic scale wave perturbations in the equatorial stratosphere, J. Atmos. Terr. Phys., 47, 769-780, 1985.

2. Larsen, M. F., and J. Röttger, Observations of frontal zone and tropopause structures with a VHF Doppler radar and radiosondes, Radio Sci., 20, 1223-1232, 1985.

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13. Holden, D. N., and M. F. Larsen, Observations of thunder with the Arecibo VHF radar, Proceedings of the URSI/SCOSTEP Workshop on Technical Aspects of MST Radars (Oct. 21-25, 1985), Handbook for MAP, 20, University of Illinois, 147-152, 1986.

14. Larsen, M. F., J. Röttger, and T. S. Dennis, Comparison of vertical velocities analyzed by a numerical model and measured by a VHF radar over an eleven day period, Proceedings of the URSI/SCOSTEP Workshop on Technical Aspects of MST Radars (Oct. 21-25, 1985), Handbook for MAP, 20, University of Illinois, 44-47, 1986.